

TEM OBSERVATIONS OF AMORPHIZED SILICATE-PEROVSKITE, AKIMOTOITE AND Ca-RICH MAJORITE IN A SHOCK-INDUCED MELT VEIN IN THE TENHAM L6 CHONDRITE. Zhidong Xie and Thomas G. Sharp. Geological Sciences Department, Arizona State University, Tempe, AZ 85287, U.S.A. zhidong.xie@asu.edu, tom.sharp@asu.edu.

Introduction: Tenham is a famous highly shocked L6 chondrite. Previous studies revealed a series of high-pressure minerals in the melt vein, including ringwoodite, majorite, wadsleyite, magnesiowüstite, akimotoite, silicate-perovskite, and hollandite-structured plagioclase [1-8]. These high-pressure minerals have been studied intensively in static high-pressure experiments [9,10]. The presence of glassy plagioclase and polycrystalline ringwoodite in Tenham indicates a shock stage of S6 ($P > 45\text{--}55$ GPa) based on shock classification of ordinary chondrites [11]. However, shock pressure also can be inferred from crystallization pressure of the melt at ~ 25 GPa, based on the phase equilibrium data [12-14]. The duration of the melt-vein solidification can be estimated based on simple thermal models [15, 16].

The goal of this study is to characterize the mineral assemblages in the melt veins of Tenham, using TEM, to constrain crystallization and to see how the crystallization pressures are related to the shock pressure inferred from the calibration of Stöffler et al [11].

Methods: Field-emission scanning electron microscopy (FESEM) is used to characterize the textures of a melt vein in a thin section of Tenham. A 3-mm dist, including a 600 μm wide melt vein, was cored from the thin section to make TEM sample. TEM imaging techniques were employed to characterize the micro-texture of the veins and the microstructures of the vein minerals. Mineral phases were identified on the basis of selected area electron diffraction (SAED) patterns and quantitative energy dispersive X-ray spectroscopy (EDS).

Results: The mineralogy and the micro-texture of the crystallized silicate melt at the vein edge differ from those of the vein center. The vein-edge region is ~ 30 μm wide and consists of a mixture of equant grains, non-equant crystals, and a few rounded metal-sulfide droplets (Fig. 1). TEM imaging and electron diffraction show that the equant grains are amorphous silicate. Quantitative EDS analysis gives the composition $\text{Na}_{0.08}\text{Fe}_{0.16}\text{Mg}_{0.82}\text{Ca}_{0.03}\text{Al}_{0.05}\text{Si}_{0.93}\text{O}_3$, which is similar to the composition of matrix majorite and consistent with the composition of silicate perovskite. The morphology and composition are similar to the vitrified silicate-perovskite in the Acfer 040 chondrite [17] and in the Zagami achondrite [15]. Unlike the previously reported silicate-perovskite in Tenham [7], which formed by a solid-state transformation of enstatite, we interpret these amorphous grains as silicate-perovskite that crystallized from silicate melt at high

pressure. These perovskites vitrified after pressure release, probably under elevated post-shock temperature conditions or possibly during sample preparation. The principle non-equant crystal in the vein edge is ringwoodite. EDS analysis shows that the ringwoodite ($\text{Fe}_{0.7}\text{Mg}_{1.3}\text{Al}_{0.02}\text{Si}_{0.98}\text{O}_4$) is rich in Al_2O_3 and FeO comparing to the host olivine (Fa_{26}) and the polycrystalline ringwoodite, indicating that it crystallized from the melt. Akimotoite ($\text{Fe}_{0.12}\text{Mg}_{0.89}\text{Al}_{0.05}\text{Si}_{0.96}\text{O}_3$), which occurs along with ringwoodite, forms long crystals that are partially vitrified and surrounded by silicate glass. Majorite was also found beside amorphous silicate-perovskite.

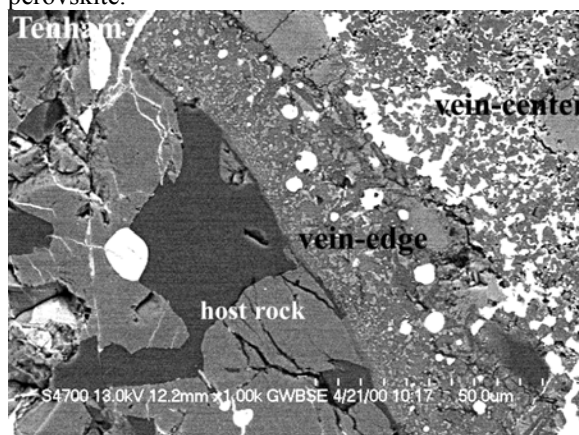


Figure 1. FESEM image shows two different textures and mineral assemblages in the melt vein. Vein edge consists of vitrified silicate perovskite + ringwoodite + akimotoite + majorite with less metal-sulfide. The vein center consists of equant majorite + magnesiowüstite with irregular metal-sulfide.

The center of the melt vein (550- μm wide) consists of equant silicate crystals and irregular-shaped metal sulfide blebs (Fig. 1). The equant grains are majorite, consistent with previous studies of the Tenham [2-7]. Majorite occurs as idiomorphic crystals ranging in size from 2–5 μm . EDS analysis gives the majorite the composition $\text{Na}_{0.03}\text{Fe}_{0.15}\text{Mg}_{0.77}\text{Ca}_{0.06}\text{Al}_{0.03}\text{Al}_{0.06}\text{Si}_{0.94}\text{O}_3$, which is rich in Al_2O_3 , CaO, and Na_2O comparing to the Al-free host enstatite. Irregular crystals of magnesiowüstite ($\text{Mg}_{0.68}\text{Fe}_{0.31}\text{Cr}_{0.01}\text{O}$) are found in the interstitial channels between the majorite grains. TEM imaging and diffraction show that tiny magnetite crystal-lites (up to 20 nm in size) are intergrown throughout the magnesiowüstite (500 nm in size). Interstitial silicate glass occurs between the equant majorite grains.

The melt vein also encloses sub-rounded fragments of the host chondrite that have been transformed to

polycrystalline high-pressure silicates [1-4]. Here we report the occurrence of Ca-rich majorite in the edge of one 200- μm -diameter fragment. The Ca-rich majorite occurs as a symplectitic intergrowth with a Ca-poor amorphous silicate phase (Fig. 2). The diffraction patterns indicate the garnet structure. The Ca-rich majorite ($\text{Na}_{0.01}\text{Fe}_{0.09}\text{Mg}_{0.67}\text{Ca}_{0.21}\text{Al}_{0.02}\text{Si}_{1.00}\text{O}_3$) is CaO-rich and FeO-poor comparing to matrix majorite. Similar symplectitic majorite was reported in 1979 [2]. The texture and composition of Ca-rich majorite suggest that it formed by the breakdown of a Ca-pyroxene precursor. Polycrystalline grains of hollandite-structured plagioclase ($\text{Na}_{0.22}\text{Fe}_{0.06}\text{Mg}_{0.08}\text{Ca}_{0.16}\text{Al}_{1.10}\text{Si}_{2.96}\text{O}_3$) also occur within the melt vein.

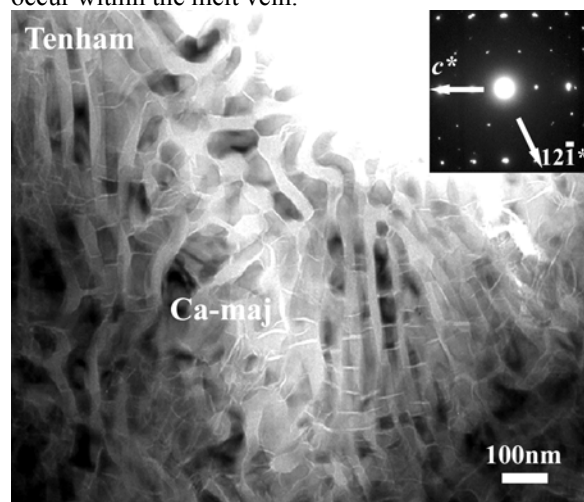


Figure 2. TEM Bright-field image shows a symplectitic intergrowth of Ca-rich majorite and an amorphous Ca-poor silicate phase. The inset SAED pattern is from the dark-contrast Ca-majorite.

Dissucussion: Based on the majorite + magnesio-wüstite assemblage that occurs throughout the melt-vein center and the phase diagram for Allende [18], the crystallization pressure of the melt vein center can be constrained at 23 to 25 GPa. However, the silicate-perovskite + akimotoite + ringwoodite + majorite assemblage in the melt-vein edge region is more complicated because this assemblage is not predicted by the Allende phase diagram [18]. Akimotoite is subsolidus phase that is stable with ringwoodite at 18 to 25 GPa in the enstatite-forsterite system [19]. Therefore akimotoite must represent metastable crystallization. The lower-pressure stability limit of silicate perovskite in the Allende system is 25 GPa, which is the same as the upper stability limit of ringwoodite. Therefore, the crystallization pressure for the melt vein edge studied is approximately 25 GPa. The difference in texture and mineralogy between the melt-vein center and edge may be the result of quench rate, where the more rapidly cooled edge resulted in a metastable assemblage. Another possible explanation is that the vein edge has

a different composition than the vein center, which could explain the higher metal sulfide content of the vein center (Fig. 1).

The crystallization pressure (23-25 GPa) implied by the two mineral assemblages is much lower than the pressure (>50 GPa) of shock stage S6 [11]. This implies that either the shock pressure was 25 GPa and the shock calibration for S6 is wrong, or the melt vein crystallized during pressure release at 25-23 GPa as the shock pressure dropped from > 50 GPa. Crystallization during release should result in a decrease in the crystallization pressure from the vein edge to the vein center. The maximum difference in crystallization pressure implied by the mineralogy in Tenham is ~ 2 GPa. Based on thermal models for melt-vein solidification [15], a 600- μm wide melt-vein crystallizes in approximately 20 micro-second. It seems unlikely that the melt vein crystallized during 20 ms of pressure release with only drop in pressure of about 2 GPa. However, if we assume that the crystallization pressure was constant at about 25 GPa, then the melt vein crystallized under equilibrium shock conditions and the crystallization pressure is the equilibrium shock pressure.

Conclusions: The melt vein in Tenham crystallized at ~ 25 GPa, over a period of about 20 ms. Crystallization is unlikely to have occurred during pressure release, therefore the crystallization pressure represents the equilibrium shock pressure.

References: [1] Binns et al. (1969) *Nature* 221, 943-944. [2] Price et al. (1979) *Contrib. Mineral. Petrol.* 71, 211-218. [3] Putnis and Price (1979) *Nature* 280, 217-218. [4] Madon and Poirier (1983) *PEPI* 33, 31-34. [5] Mori and Takeda (1985) *LPS XVI*, 579. [6] Langenhorst et al. (1995) *Geochim. Cosmochim. Acta* 59, 1835-1845. [7] Tomioka and Fujino (1997) *Science* 277, 1084-1086. [8] Tomioka et al. (2000) *Geophys. Res. Lett.* 27, 3997-4000. [9] Ringwood A.E. (1958), *GCA*, 15, 18-29. [10] Irifune T. (1993), *The Island Arc*, 2, 55-71. [11] Stöffler D. et al. (1991) *GCA*, 55, 3845-3867. [12] Chen M. et al. (1996) *Science* 271, 1570-1573. [13] Xie Z. and Sharp T. G. (2000) *LPS XXXI*, 2065.pdf. [14] Sharp T.G. et al. (2001) *LPS XXXII*, 2159.pdf. [15] Langenhorst and Poirier (2000) *EPSL* 184, 37-55. [16] Sharp T. G. et al. (2002) *MAPS*, 37, A129. [17] Sharp T. G. et al. (1997) *Science* 277, 352-355. [18] Agee C. B. et al. (1995) *JGR*, 100, 17,725-17,740. [19] Gasparik T. (1992) *JGR*, 97, 15181-15188. [20] Oguri K. et al. (1997) *PEPI*, 104, 363-370.